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TECHNICAL EVALUATION REPORT

Paper T1; AGARD Conference Proceedings CP-584

Fluid Dynamics Panel Symposium on

"THE CHARACTERISATION AND MODIFICATION OF WAKES FROM LIFTING VEHICLES IN FLUIDS"

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NORTH ATLANTIC TREATY ORGANIZATION

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SUMMARY

The Fluid Dynamics Panel of AGARD arranged a Symposium on "The Characterisation and Modification of Wakes from Lifting Vehicles in Fluids," on 20-23 May 1996 in Trondheim, Norway. The purpose of the Symposium was "... *to review and discuss recent developments in wake research for aircraft and the implications for air traffic regulations,*" with a clear emphasis on the hazard of vortex encounters in civil aviation. Sessions were devoted specifically to operational procedures and aircraft spacings in airport terminal areas; to the aerodynamic interactions between trailing vortices and following aircraft; to trailing vortex structures, instabilities, atmospheric effects on wakes, and vortex breakdown; and to miscellaneous issues, such as vortices generated by other vehicles and the interactions between vortex wakes and engine exhausts. The Symposium was unclassified, and it was rather unusual with respect to the broad range of interests of the active participants: representatives of regulatory agencies; aircraft manufacturers and operators; and research scientists engaged in flight tests, flight simulations, and basic experimental and theoretical fluid dynamics. Thirty-seven papers were presented at the meeting (see Appendix). An overview of the Symposium and some general conclusions and recommendations are given in this Evaluation Report.

1. INTRODUCTION

Vortical aerodynamic flows comprise an important and on-going part of the AGARD Fluid Dynamics Panel's terms of reference, activities, and expertise. In 1990, the Panel held a Symposium on "Vortex Flow Aerodynamics" [1], which was primarily concerned with near-field vortical flows and separation on military aircraft and missiles. That meeting emphasized leading-edge vortices of highly-swept wings and slender bodies at high angles of attack, and their effects on performance, stability, control, and structural design loads. Figure 1, from Paper No. 1 of the present Symposium, schematically indicates some of the basic features of this class of problems. On the other hand, the present conference focused mostly on the vortex wakes of large civil jet transports (represented by Fig. 2 from Paper 26), and on the hazards that they present to following aircraft. Both practical problems share many common fluid dynamic aspects, of course; and both meetings included papers on fundamental aspects of vortical flows and their control that are applicable to all classes of flight vehicles.

The theme of the present Symposium was listed in the program as follows:

> "The aim of the symposium is to review and discuss recent developments in wake research and the implications for air traffic regulations. The aircraft separation necessary to avoid the hazard of vortex encounters must be realized despite the increasing number of airports and of commercial aircraft per airport. Economically efficient aircraft spacing requires an accurate prediction of vortex formation, evolution, decay and breakdown. Atmospheric stratification and compressibility affect aircraft wakes at cruising altitude and also near the ground during takeoff and landing. In addition, wakes are getting more and more

important in the detection of military aircraft. Therefore, techniques leading to a premature vortex decay and breakdown are of great interest. New experimental techniques and theoretical methods have been developed for the improvement of wake prediction. These tools include Direct Numerical Simulation (DNS) and inflight measurements."

This statement is an effective synopsis of the Symposium, except for a few papers that were given on other, closely related topics. Also, it may be mentioned that contributions were solicited on the role of vortex wakes in the detection of military aircraft and submarines, but none was offered to the Program Committee. On the other hand, papers on helicopter wakes, which share many vortical features with aircraft wakes, were not solicited. Thirty-seven papers were presented in eight technical sessions that spanned 3-1/2 days, and the meeting concluded with the Technical Evaluator's preliminary comments and a general discussion.

2. THE VORTEX WAKE PROBLEM AND ITS CONSEQUENCES

As noted above, the primary problems that were addressed by the Symposium stem from the safety hazard of an aircraft encountering the strong vortex wake generated by a large aircraft flying ahead of it. It is well known that the trailing wake of a lifting body rolls up into a pair of strong, counter-rotating longitudinal vortices that persist for *many* body dimensions downstream. The strength of these trailing, ribbon-like vortices is approximately proportional to the weight of the aircraft that generated them, and they represent a severe atmospheric disturbance to other aircraft that happen to traverse their path -- accidents have resulted and lives have been lost. This vortex-wake problem and the associated safety issues came to the fore in the late 1960s with the introduction of "jumbo jets" that were much larger and heavier than other aircraft in common service.

A flurry of basic and applied research activity in the 1970s produced a better understanding of the far-wake structure and its perverse persistence, and of the magnitude of the forces and moments experienced by aircraft encountering trailing vortex wakes. However, little success was achieved in reducing this invisible hazard, other than avoiding the flight path of large aircraft. But since aircraft must share the airspace near airports, the only solution up to now has been to maintain a suitably-large spacing between aircraft during takeoff and landing. This spacing requirement, especially for landings, constrains the operational capacity at a growing number of congested commercial airports around the world, and future aircraft of even greater size and weight will exacerbate the costly delays between landings. Therefore, there is a keen practical interest in the fluid dynamics of almost all aspects of vortex wakes. This includes their formation, control, evolution, transport, decay, and breakdown; the interactional aerodynamic effects on aircraft that encounter vortex wakes; meteorological and ground-interaction effects on vortex structure and breakdown; and modeling, computing, detecting, and measuring trailing wakes.

The first two papers set the stage for the Symposium very well by defining and explaining (1) the relevant fluid dynamic phenomena of trailing vortical wakes, (2) the effects of vortex encounters by following aircraft, and (3) the practical, operational consequences of assuring that severe vortex encounters are avoided. The third point is brought out very clearly by Mr. Gerald Mack in Paper 2, describing the commercial air traffic control procedures and separation criteria that have evolved in the United States to avoid unsafe vortex encounters.

Mack notes that the majority of wake vortex, or wake turbulence, encounters occur during final approach, which is characterized by airplanes flying through a relatively narrow corridor. Both the "leader" and "follower" aircraft in the U.S. are classified as "heavy," large," or "small." Different minimum separation distances are in effect for each combination of aircraft. Different operating environments, *i.e.,* instrument or visual meteorological conditions (IMC and VMC, respectively), also affect the flight paths. For example, Air Traffic Control maintains horizontal and vertical separation between airplanes under instrument flight rules (IFR), whereas the pilot of the following airplane is responsible for maintaining safe separation under visual flight rules (VFR). The prescribed IFR horizontal separation distances are typically larger than those maintained by pilots for VFR landings. Significantly, there have been *no* accidents in the US while IMC operations were in effect and the prescribed procedures were followed, and none have occurred during VMC operations *when the following pilot flew at or above the flight path of the leading aircraft.*

The prescribed IFR horizontal separation distances in the U.S. now range from 3 to 6 miles, depending on the sizes of the two aircraft. These minimums represent a key limiting factor at many congested airports, and travelers know from practical experience that delays at one airport often ripple throughout the entire air traffic system. Therefore, pressure is mounting to reduce the existing separation criteria, without compromising safety. Although much has been learned over the past 25 years, Mack points out that:

> "... Refining existing separation criteria requires consideration not only of wake turbulence-related aircraft categories, ATC procedures, and piloting procedures, but also of a variety of issues such as radar limitations, runway occupancy time, flight path constraints, airport configuration, and traffic mix."

According to Mack, the most important unresolved wake issues are:

> "1. The near-field characteristics of a wake and how these influence the far-field characteristics;
>
> 2. The influence of meteorological conditions on the far-field characteristics of a wake."

Subsequent papers addressed these points in some detail, but they remain poorly understood.

Finally, Paper 2 introduces an automated-system concept that is designed to adjust dynamically and adaptively the separation criteria based on more detailed information about the participating aircraft, and on measurements of local meteorological conditions and trajectories of wake vortices during flight operations. The program is called "Aircraft Vortex Spacing System (AVOSS)," and it is described in more detail in Paper 23 by D.A. Hinton.

Comments on the European regulatory viewpoint are given in Paper 3 by Mr. Klaus Koplin, who describes the activities of the 26-member Joint Aviation Authorities (JAA) and its relationship with other European organizations concerned with civil aviation regulations. Wake vortex hazards are worrisome in Europe and must be considered in planning for air traffic growth, but JAA does not consider this an urgent safety problem at present. Paper 4 describes the International Civil Aviation Organization (ICAO) size classifications and separation distances, which are slightly different from those of the US Federal Aviation Administration (FAA). The author also discusses how a vortex detection and warning system could be used to improve the situation.

Papers 12, 14, 21, 22, and 23 also help to define more clearly the vortex hazard problem by analyzing actual and theoretical rates of encounters; by addressing training, simulation, and regulation issues and their consequences; and by discussing ways of improving operational efficiency and airport capacity. These papers contain important considerations for future courses of action, which will be mentioned again in Section 4.2

3. THE PHYSICS OF VORTEX WAKES

In simple terms, the generation of lift by an aircraft creates strong concentrated trailing vortices, which should be avoided by other aircraft. The Keynote Speaker points out in Paper 1 the distinction between vortex wakes created by flow separation from highly-swept leading edges, such as delta wings (see Fig. 1), and vortex wakes typical of subsonic transport aircraft; *e.g.*, Figs. 2 and 3. The former wakes dominated the 1990 Symposium [1], whereas the present Symposium strongly emphasized the latter. The majority of the present papers address some aspects of vortex aerodynamics, and they can be grouped for discussion into the five subcategories listed below.

3.1 Initial Wake Formation and Rollup

Papers 5, 9, 15, 25, and 27 present detailed wake survey measurements in the initial rollup region (see Fig. 4). Paper 29 contains smoke flow visualizations behind a free-flight model of an Airbus A300-B2 aircraft, extending beyond the wake-rollup region. Paper 27 reports on the effects of mass injection near the origin of the tip of a simple rectangular wing, resurrecting an idea promoted in the early 1970's [2] with limited success. Papers 5, 9, 25, and 29 provide data for wings with flaps deployed, which produce the multiple-vortex patterns indicated in Fig. 3, and Paper 15 analyzes the measurements behind a wing, nacelle, and propeller combination. These data should be especially valuable data for checking theoretical and numerical methods.

Papers 6, 7, 8, 9, 20, and 25 contain theoretical or numerical methods for analyzing initial wake rollup. Paper 6 analyzes in the Trefftz plane the interaction between a pair of concentrated longitudinal vortices and the vortex sheet rolling up behind an elliptically loaded wing, with a view toward determining the effectiveness of large vortex generators on the upper surface of the wing in destabilizing the vortex wake downstream. Paper 7 is a Computational Fluid Dynamics (CFD) study, using two different turbulence models, of (1) tip vortex formation and (2) the decay of an axisymmetric vortex in the far field. Although good qualitative results are obtained, neither turbulence model produces the high levels of suction observed on the wing tip (see Fig. 7 of Paper 7). However, it may be mentioned in passing that Dacles-Mariani, *et al* [3] attained excellent quantitative results for this same case using many more grid points and a higher-order CFD algorithm.

3.2. Instability, Decay, and Breakdown

This topic comprised the largest component of the symposium, representing the primary focus, or at least a significant element, of Papers 6, 10, 11, 17-20, 30-32, 34, and 35. Considerable theoretical research has been expended over the past 25 years since the landmark paper by Crow [4], which predicted the growth of sinusoidal instabilities in trailing vortex pairs. The Crow Instability is generally accepted as the mechanism for the observed transformation of contra-rotating straight trailing vortices into a wavy pattern, and eventually into a train of vortex rings that quickly disintegrates.

As noted in the previous section, Paper 6 analyzes the interaction between prescribed concentrated longitudinal vortices and the trailing vortex sheet of an elliptically-loaded wing. The authors report on the optimum location and strength of the prescribed vortices for promoting the Crow instability far downstream. Paper 17 analyzes the linear stability, *à la* Crow, and nonlinear transient growth of *two* vortex pairs, representing an aircraft with high-lift flaps deployed. The author finds additional modes for the periodic instabilities produced by the addition of flap-edge vortices, and indicates that the spanwise location of the outboard edge of the flap is an important parameter in controlling the wake breakdown.

Papers 18, 19, 28, and 30 present impressive Direct Numerical Simulations (DNS) of the Crow Instability in the Decay Region (see Fig. 4). This is done in Paper 18 by immersing several pairs of theoretical line vortices in a large "box" of three-dimensional atmospheric turbulence. Each individual vortex is close enough to its own "partner" to interact with and develop sinusoidal instabilities, but the vortex pairs are far enough apart to not interact with other pairs. Owing to the randomness of the turbulence in the box, the different pairs develop into different detailed trains of vortex rings, replicating what is observed in actual contrails. Paper 19 is a two-dimensional DNS simulation of the time-evolution of a pair of ideal vortices with laminar viscous cores, subjected to a small perturbation disturbance. Marching the calculations forward in time, the authors are able to link the vortex pair behavior with the Crow instability. Paper 28 studies the effects of atmospheric turbulence, ground interference, and crosswinds on vortex instability and decay. Large-scale atmospheric turbulence is found to promote an inviscid, long wave-length instability, whereas small-scale turbulence increases the diffusion of the viscous core.

Paper 30 uses a new laminar three-dimensional method, periodic in the streamwise direction, to study some properties of the Crow Instability in concentrated pairs and rolling-up pairs of trailing vortices. Paper 34 includes a numerical study of Reynolds number on the evolution of pairs of laminar trailing vortices; the Crow Instability is also reproduced.

Paper 20 is also able to reproduce the Crow instability by superimposing small perturbations on a quasi-steady flow field that is constructed by three-dimensional vortex filaments with analytical viscous cores. The author cites the results for sensitivity to wave number and insensitivity to Reynolds number as evidence that the Crow instability is purely kinematic kind, and an absolute instability. Paper 35 uses the vortex filament technique of Paper 20 to compute the initial rollup of the vortex wake behind a Boeing 747 aircraft in cruise, *including* the entrainment (or non-entrainment in some cases) of the engine exhaust. A Large Eddy Simulation (LES) technique carries the solution far downstream to the initial collapse of the vortex pair. The role of buoyancy, stratification, and atmospheric and aircraft boundary-layer turbulence on the onset of tip vortex decay is investigated, in what appears to be the first attempt to study the lifespan of the wake from formation to breakdown with all these effects included.

Paper 31 is an analytical two-dimensional, inviscid study of the basic effects of atmospheric compressibility and density stratification (buoyancy) on the vertical motion of a vortex pair. Examples representing the wake of a Boeing 747 aircraft show how the descent of the vortex pair can be accelerated or decelerated by atmospheric effects.

Experimental results related to vortex decay and breakdown are presented in Papers 10, 11, 13, 32, and 34. However, there is no counterpart for the Decay Region of the detailed data of Papers 5, 9, and 25 in the Wake Rollup Region (see Fig. 4); only Paper 34 directly complements the theoretical and numerical studies mentioned above. Paper 34 includes Digital Particle Image Velocimetry measurements of the decaying wake vortex of a wing in a towing tank, through the onset of the Crow Instability, and some information is given concerning the effects of drag-producing devices on the far-wake development. Paper 32 studies the spiral breakdown of a wing tip vortex in the presence of an adverse axial pressure gradient downstream of the wing, tested in a water tunnel. A numerical study of the three-dimensional Euler equations provides some additional physical insight into the vortex breakdown for this special problem. The impressive field measurements described in Papers 10, 11, and 13 were made near the ground; therefore, they are discussed in Section 3.3 below.

3.3. Ground and Crosswind Interactions

Papers 10 and 13 contain field measurements of the structure, trajectory, and strength of transport aircraft wakes near the ground during normal landing operations. Paper 11 examines wakes of Boeing 727, 757, and 767 aircraft during low-altitude flyovers, with and without flaps deflected, and mostly under conditions of persistent crossflow. The ground-based measurement techniques include hot wire and propeller anemometers mounted on towers (Papers 11 and 13, respectively), a form of Laser Doppler Velocimetry called coherent laser radar, or LIDAR (Papers 10 and 11), and an acoustic Doppler backscatter system called Monostatic Acoustic Vortex Sensing System, or MAVSS (Paper 11). Results in all three papers appear to correspond to the Vortex Region and Decay Region of Fig. 4 (note that in Fig. 4 the *distances* are typical for *cruise*, not landing conditions).

The large data base described in Paper 11 provides some information on the effect of meteorological conditions on vortex lifetime. Paper 10 reports on data collected at five sites near Heathrow Airport for a range of atmospheric conditions and aircraft heights. More complex vortex velocity profiles were measured in the Boeing 747 wakes than in the conventional ones of the B-757, and this deserves further attention. The authors also report occasional instances of vortices rebounding after descending normally. Paper 13 also reports rebounding, which is attributed to ground boundary layer effects and the creation of secondary vortices.

The impressive DNS calculations reported in Paper 28 (see Section 3.3) reproduce this rebounding phenomenon and the creation of secondary vortices, and Paper 34 gives some indication of the large effects of vertical wind shear on the Crow Instability. Thus the numerical tools to study ground and interactions in more detail seem to be available, although further validations and algorithm improvements are still required.

3.4 Forces and Moments on Following Aircraft

The fundamental characteristics of wake formation and decay are important ingredients in the vortex hazard problem, but the hazard manifests itself in the response of the aircraft that encounters the wake. Furthermore, changes in the detailed structure of the vortex in the Rollup Region (see Fig. 4) do not always significantly affect the total angular momentum in the wake. Unfortunately, the important topic of the forces and moments on following aircraft did not receive much attention at the present Symposium, addressed only in Papers 14 and 26.

Paper 14 is a flight simulator study of the response of a Boeing 737 aircraft to a variety of prescribed vortex wakes and operational assumptions. The aerodynamic interaction is modeled rather simply; but trends were obtained for stick-free response, the response of the aircraft controlled only by the autopilot, and response with a "math pilot" designed to keep the wings level.

Paper 26 summarizes extensive recent test results obtained in the largest NASA wind tunnel, in which simplified wing models of various spans were mounted at one-half and one mile scale distances downstream of 0.03 scale

models of B-747 and DC-10 aircraft. For these two generating models, conventional landing configurations, unconventional flap configurations, and several candidate vortex-alleviation devices were tested. The lift and rolling-moment data on the following models are used to validate a vortex-lattice prediction method. The reader is referred to Ref. 5 by the same author for a more complete review of some of the successes and failures of past attempts to reduce the rolling moment response. In some cases, significant reductions have been obtained in rolling moment induced on the following wings, but unfortunately, not without performance penalties.

3.5 Exhaust/Vortex Interactions

The interaction of the engine exhausts with the trailing vortex wake does not appear to contribute significantly to the wake vortex hazard problem, although the possibility of triggering wake instabilities remains somewhat open. On the other hand, exhaust/vortex interactions can be important in assessing the impact of aircraft emissions and in the infrared detection of aircraft. Also, at high altitude, water vapor in the exhaust often provides an effective visualization of the wake location and breakdown.

As noted in Section 3.2, Paper 35 uses a vortex filament technique to compute the initial rollup of the vortex wake behind a Boeing 747 aircraft in cruise, and an LES technique carries the solution far downstream to the initial collapse of the vortex pair. Passive tracers released in the turbine core and in the bypass region show that the engine exhaust does not always become completely entrained in the trailing tip vortices within the Rollup Region (see Fig. 4). This calculated result agrees with and helps explain recent flight measurements.

The last paper of the Symposium, Papers 37, studies the dynamics of jet/wake interaction in the Rollup Region of cruising flight. Arguments based on characteristic interaction parameters lead to the conclusion that the jets have almost no effect on the vortex wake. The authors then use a one-dimensional integral model for the jet and a fully-developed vortex model for the wake. These models lead to complete entrainment of the engine exhausts into the wake vortices. The authors conclude that distortion of the jet plume by vortex shearing becomes important as the jets are drawn into the center of the vortices, and that this effect should be investigated.

4. ALLEVIATING THE PROBLEM

At the present time, there are three ways to alleviate the hazard of encounters between an aircraft and a trailing vortex wake. The first is to wait, passively; that is, to maintain a suitably-large separation distance between aircraft. The consensus of Papers 1-4 seems to be that today's separation standards and procedures are adequate, *if followed*. However, economic pressures to *decrease* separations will inevitably grow over time. On the other hand, the introduction of even larger aircraft will exacerbate the vortex hazard, necessitating *increased* separations and offsetting some of the economic advantages of the larger vehicles. The alternatives in the highly-competitive area of air transportation are to either (1) modify the vortices without sacrificing performance, or (2) modify the flight procedures without compromising safety.

4.1 Modifying the Vortices.

Papers 6, 17, 26, 27, 30, 34 join the fluid dynamics research community's perennial crusade to modify the vortices. Techniques considered include generating additional longitudinal vortices to destructively interfere with the tip vortices, altering the spanwise extent of the flaps, altering the flap deflections in different spanwise segments, injecting air at the wing tip to destabilize the vortices, perturbing over time the spanwise circulation distribution, and altering the spanwise drag distribution. Physical understanding is improving with the aid of advanced CFD techniques and new detailed measurements, and promising results are shown. However, modern jet transports are highly optimized for weight, cost, and performance, and a practical solution that does not sacrifice these parameters has yet to emerge.

4.2 Modifying the Flight Procedures.

Current air traffic procedures for aircraft spacing are essentially statistically designed to preclude a dangerous aircraft-wake encounter under worst-case conditions. An alternative is to adapt the flight procedures case by case, on the basis of better knowledge of the potential hazard in individual flight situations and/or of the particular meteorological conditions at the time. Some aspect of this general theme is addressed in Papers 2-4, 12, 14, 21-23. In particular, Paper 23 describes an Aircraft Vortex Spacing System (AVOSS) under development by NASA that dynamically integrates current and predicted

local weather conditions, wake vortex transport and decay information, wake vortex sensor data obtained within the flight corridors, and knowledge of acceptable vortex strengths to produce appropriately-reduced separation distances.

Ideally, the AVOSS system would provide time-dependent spacing criteria to automated Air Traffic Control systems with sufficient lead time to influence aircraft arrival scheduling. The paper describes the overall concept and the challenges of the various subsystems, such as weather prediction, vortex detection, and hazard prediction or assessment. CFD simulations of wake vortex and development and meteorological forecasts are being used to develop fast prediction algorithms, and LIDAR and other (unspecified) ground-based sensor technologies are being investigated for detecting and tracking wake vortices. A field demonstration is planned for the year 2000.

If successful, and if adapted, AVOSS could enable airport capacities to be increased in the next century by means of the weather-dependent reduced aircraft spacings. On the other hand, past studies [6] at one major European airport, Schiphol/Amsterdam, indicate that the variability in winds and the uncertainties in predicting them may well force the air traffic controllers to apply the standard, large separations most of the time, thus negating the potential advantage of a vortex advisory system.

Finally, other new technologies, such as Global Positioning System (GPS), are developing rapidly, and these developments may present new opportunities for varying the flight procedures advantageously. For example, Rossow [7] has recently suggested that the aircraft separation distances could be reduced by using GPS to constrain the flight paths to corridors more narrow than the present ones. The argument is that AVOSS, or other vortex-avoidance systems, could be simplified by limiting where the wake vortices are located and where aircraft that might encounter them can fly.

5. RELATED TOPICS

Roughly 20% of the papers in the Proceedings of the Symposium are on other, but closely related, topics. Paper 8 summarizes the combination of discrete vortex and vortex lattice design and analysis methods for unsteady problems, including practical examples such as maneuvering aircraft, missiles, and submarines. Paper 15 gives a detailed analysis of experimental flow field surveys behind a propeller-wing configuration in low speed flow. Paper 16 is a numerical study, using an Euler CFD code, of the flowfield of a delta wing embedded in the wake of a bursting vortex generated by another delta wing. Performance enhancements by vortical effects are considered in Papers 33 and 36. Wakes shed from flapping airfoils and their interactions with shear layers are studied in Paper 33, and favorable interference effects of wing vortices in formation flight, such as the V-shaped formations of migrating birds, are described in Paper 36. Finally, Paper 24 presents a detailed study and analysis of the shifting winds surrounding the airport for the Symposium and the effects on the final stages of landing there. Most of the participants at the Symposium were glad they heard about this situation only *after* they arrived.

6. SUMMARY AND CONCLUSIONS

As noted in the Abstract, this Symposium was especially noteworthy for the wide range of authors and active participants, which included both research scientists and customers; *i.e.*, representatives of regulatory agencies, airlines, and manufacturers. However, it is somewhat surprising that little mention was made of a similar, and larger, international conference in 1991, the Aircraft Wake Vortices Conference [8], sponsored by the FAA. Nevertheless, the present Symposium disseminated more widely, and reinforced, the following existing knowledge about the vortex wake hazard of transport aircraft and their implications for air traffic regulations:

First, there is a *hazard*, and avoiding this hazard creates airport congestion, air traffic restrictions, and delays. These problems translate into higher costs for air transportation.

Second, the relevant *physics* is that aircraft produce strong vortices, whose strength is approximately proportional to the weight of the aircraft, and these vortices are perniciously persistent. Much is known about the fundamental fluid dynamics, and the Symposium participants contributed impressive new field and laboratory experiments and numerical simulations that were not available at the time of the 1991 FAA Conference. However, the details of vortex decay and breakdown are still

not fully understood. Even less is known about the influence of meteorological conditions on the far-field characteristics of a vortex wake.

Third, vortex decay *can* be enhanced, although not easily. More importantly, the far-wake structure, and its induced forces and rolling moments (the hazard), *can* be modified. However, this is also difficult to accomplish, especially without adding unacceptable weight or performance penalties that outweigh the savings of closer aircraft spacings. In other words, a practical, *engineering* solution has not yet been found.

Collectively, this knowledge would lead the optimist to conclude that aerodynamics is not a fully mature technology.

Looking ahead, short-term gains seem most likely to come from refinements to the existing systems, such as improved training, especially with respect to vertical separations, and possibly changing the weight categories (see Paper 12). These refinements can be supported by additional simulation studies, such as those reported in Paper 22.

The fluid dynamics community remains ever optimistic that a better fundamental understanding of vortex formation, decay, and breakdown will lead to practical modifications of aircraft that will reduce the hazard of vortex wake encounters. Forecasting technological progress is risky, but it seems to the writer that the ongoing search for and implementation of an *aerodynamic* solution remains a long-term challenge. Newly-emerging CFD tools revealed at the Symposium should help accelerate the process, but the numerical simulations have not been adequately validated for the most part, and the enormous new data bases are just beginning to be digested. Nevertheless, CFD appears mature enough today to complement laboratory experiments and flight tests in evaluating methods for modifying the wake vortex formation and initial rollup. The next few years should see these numerical simulations for real, complex geometries extended to the far wake. There are risks involved because of the cost of such CFD solutions, but they will still be economical compared to flight tests. In any case, they will prove to be worth the price by generating new ideas and by obtaining meaningful evaluations of vortex-alleviating devices.

The operators and regulators are more skeptical, and they are far from ready to modify air traffic control procedures based on fluid dynamics research. Understandably, they are more concerned with improved detection and avoidance procedures as a means to allow reduced aircraft separation near airports. In fact, these are the measures that are more likely to provide mid-term relief. The fluid dynamics community can help by providing better approximate models of wake decay; better models of rolling moments for various generating aircraft; better predictions and means of detecting of vortex wakes; and cheaper, more reliable weather data. Emerging information systems technology should help gather, process, and disseminate the enormous amount of data that will be generated in aircraft terminal operations.

Ultimately, the economics of airport congestion will have to be weighed against the performance penalty of modifying the vortices and the cost and complication of implementing a safe and reliable system to vary aircraft spacing dynamically. All segments of the scientific and technological communities must continue to work together to attain a better world-wide air traffic *system* in the 21st Century.

7. REFERENCES

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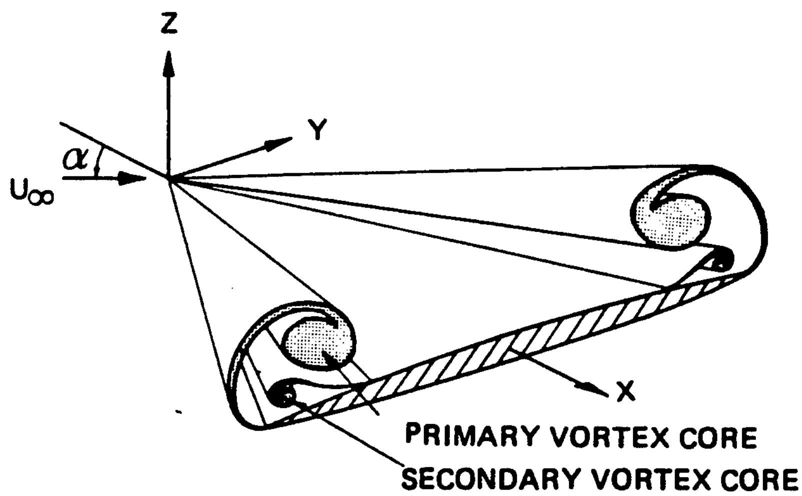


Figure 1. Schematic of flow on a delta wing with leading-edge vortices. (from Paper 1)

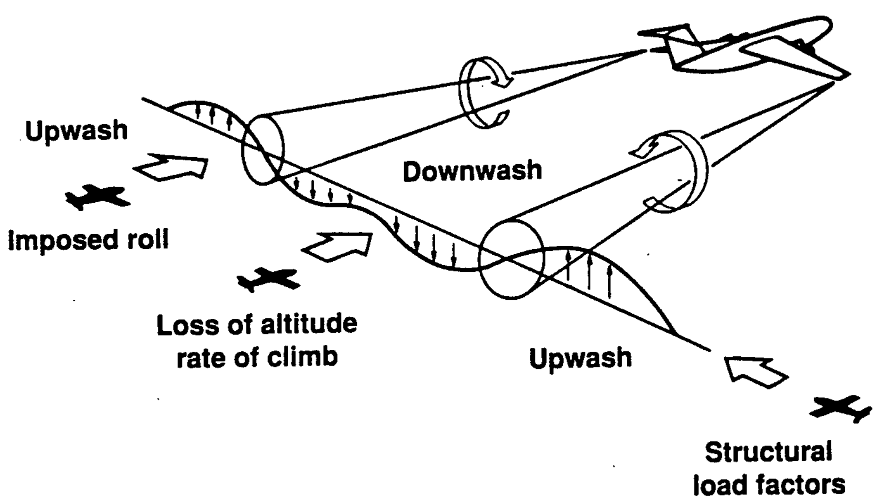


Figure 2. Schematic of generation of wake vortices from wing tips and possible encounters by following aircraft. (from Paper 26)

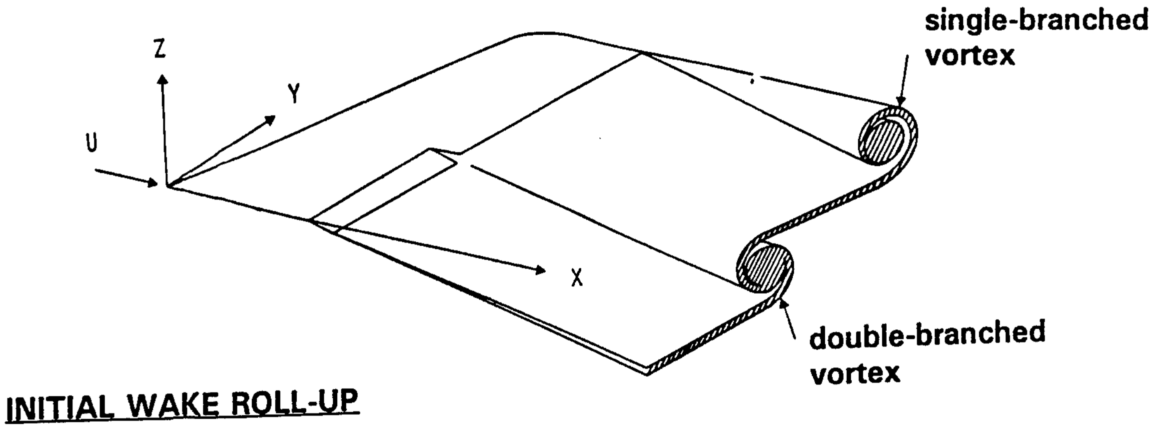
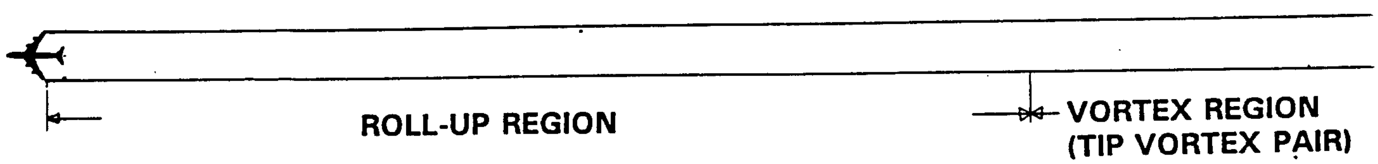


Fig. 3. Vortex wakes from a wing with flaps (from Paper 1)



- **ROLL-UP REGION**
  ~ 20 spans, 5 sec flying time, 1 km
- **VORTEX REGION**
  ≤400-500 spans, 1.5 min flying time, 20 km
- **DECAY REGION**

DANGEROUS WAKE HAZARD: **4-5 km,**
strongly dependent on atmospheric conditions

Fig. 4. Wake regions for a transport aircraft in cruise. (from Paper 1)

AGARD Fluid Dynamics Panel Meeting and Symposium on

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KEYNOTE SESSION

1. H.W.M. Hoeijmakers, "Vortex Wakes in Aerodynamics" (presented by A. Elsenaar).

SESSION I - REGULATORY VIEWPOINTS

2. G.R. Mack, "Wake Vortices' Effects and the Need for Prompt Action -- a US View".

3. K. Koplin, "Wake Vortices -- A European Regulatory View".

4. F. Brenner, "Air Traffic Control Procedures for the Avoidance of Wake Vortex Encounters -- Today and Future Developments by DFS".

SESSION II - VORTEX WAKE STRUCTURE

5. K. Huenecke, "Structure of a Transport Aircraft-Type Near Field Wake".

6. M.R. Dhanak, "The Interaction Between an Injected Vortex and a Rolling Up Vortex Sheet".

7. J.A. Eaton and M.P. O'Flaherty, "Flow Field Prediction of Three Dimensional Wing Trailing Vortices Using Advanced Turbulence Models".

8. M.R. Mendenhall and S.C. Perkins, Jr., "An Unsteady Vortex Wake Model for Manoeuvring Vehicles".

9. W.R. Graham, "Experimental Assessment of the Extended Betz Method for Wake Vortex Prediction".

10. J.M. Vaughan, D.W. Brown, G. Constant, J.R. Eacock, and R. Foord, "Structure, Trajectory, and Strength of B747 Aircraft Wake Vortices Measured by Laser".

SESSION III - AIRCRAFT/VORTEX INTERACTIONS

11. R.P. Rudis, D.C. Burnham, and P. Janota, "Wake Vortex Decay Near the Ground Under Conditions of Strong Stratification and Wind Shear".

12. D.C. Carbaugh and W.D. Forsythe, "Wake Turbulence Training and Regulation: An Industry Team Approach".

13. S.L. Abramson, and D.C. Burnham, "Ground-Based Anemometer Measurements of Wake Vortices from Landing Aircraft at Airports".

14. J.E. Vasatka, "The Dynamic Response of a Twin-Engine, Commercial Jet Transport Aircraft to Wake Vortex Encounters".

15. L.L.M. Veldhuis, and D.W.E. Rentema, "Experimental Analysis of the Vortex Wake Structure Behind a Propeller-Wing Configuration".

16. J.M.A. Longo, M. Orlowski, and D. Strohmeyer, "Flowfield of a Wing Embedded in the Wake of a Burst Vortex".

SESSION IV - VORTEX INSTABILITIES

17. J.D. Crouch, "Stability of Multiple Trailing-Vortex Pairs".

18. P.R. Spalart, and A.A. Wray, "Initiation of the Crow Instability by Atmospheric Turbulence"

19. D. Sipp, L. Jacquin, and P. Sagaut, "Simulation Numérique Directe de l'Instabilité Sinusoïdale".

20. T. Ehret, "Stability Theory for Two Wing Tip Vortices Behind Cruising Aircraft".

SESSION V - AIRCRAFT SPACING CONSIDERATIONS

21. D.C. Burnham, "Analysis of UK-Encounters 1982-1990".

22. J.J. Robinson, "A Simulation-Based Study of the Impact of Aircraft Wake Turbulence Weight Categories on Airport Capacity".

23. D.A. Hinton, "An Aircraft Vortex Spacing System (AVOSS) for Dynamical Wake Vortex Spacing Criteria".

SESSION VI - ATMOSPHERIC EFFECTS ON WAKES

24. N. Kubberud, J. Oye, and H. Norstrud, "On the Interaction Between Topographical Wind and Landing Aircraft".

25. A.C. DeBruin, S.H. Hegen, P.B. Rohne, and P.R. Spalart, "Flow Field Survey in Trailing Vortex System Behind a Civil Aircraft Model at High Lift".

26. V.J. Rossow, "Measurements in Vortex Wakes Shed by Conventional and Modified Subsonic Aircraft".

27. J.D Jacob, D. Liepmann, and O. Savas, "Natural and Forced Growth Characteristics of the Vortex Wake of a Rectangular Airfoil".

28. A. Corjon, F. Risso, S. Stoessel, and T. Poinsot, "Simulations Numeriques Directes Tridimensionnelles de Tourbillons de Sillage: Effets de la Turbulence Atmospheriques et Rebond avec Vent Lateral".

29. P. Coton, "Caractérisation et Modélisation du Sillage des Avions á partir d'Essais en Vol de Maquettes en Laboratoire".

SESSION VII - VORTEX BREAKDOWN

30. S.C. Rennich, and S.K. Lele, "Direct Numerical Simulation of the Breakdown of Aircraft Wake Vortices".

31. R. Stuff, "The Inviscid Motion of a Vortex Pair in a Compressible and Stratified Atmosphere".

32. S.H. Backstein, "Experimental and Numerical Results on Spiral Vortex Breakdown".

33. C.M. Dohring, M.F. Platzer, D.D. Jones, and I.H. Tuncer, "Computational and Experimental Investigation of the Wakes Shed from Flapping Airfoils and Their Wake Interference/ Impingement Characteristics".

SESSION VIII - MISCELLANEOUS ISSUES

34. D.P. Delisi, G.C. Greene, W.P. Pierce, R.E. Robins, and R. Singh, "Recent Laboratory and Numerical Trailing Vortex Studies".

35. T. Gerz, and T. Ehret, "Wake Dynamics and Exhaust Distribution Behind Cruising Aircraft".

36. D. Hummel, "The Use of Aircraft Wakes to Achieve Power Reductions in Formation Flight".

37. L. Jacquin and F. Garnier, "On the Dynamics of Engine Jets Behind a Transport Aircraft".